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**AVHRR-Based Polar Pathfinder Products: Evaluation,  
Enhancement**

**and Transition to MODIS**

(NASA Grant: NAG5-6666)

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This the final report for the NASA Grant NAG5-6666. The four sections of this report:

1. Introduction
2. APP Products: A brief description of the APP products
3. Validation: The validation efforts of this project
4. Summary

Copies of four papers associated with the validation effort are attached.

Spatial and temporal variability of satellite-derived cloud and surface characteristics during FIRE-ACE, J.A. Maslanik, J. Key, C.W. Fowler, T. Nguyen, and X. Wang. In press: Journal Geophysical Research

SPATIAL AND TEMPORAL VARIATIONS IN MONTHLY AVERAGED CLOUD COVER BASED ON AVHRR POLAR PATHFINDER DATA. Sheldon Drobot, James Maslanik, and Charles Fowler. To be presented and upcoming AMS conference.

Intercomparison Between in situ and AVHRR Polar Pathfinder-derived Surface Albedo over Greenland. Julianne C. Stroeve, Jason E. Box, Charles Fowler, Terence Haran, and Jeffrey Key. Accepted for publication: Remote Sensing of the Environment.

Assessment of Greenland Albedo Variability from the AVHRR Polar Pathfinder Data Set. Julianne Stroeve. Submitted: Journal of Geophysical Research.

Also attached are copies of the year 1 and 2 interim reports.

## 1. Introduction

Study of the environment has historically been done with observations and measurements in relatively few local areas. While some of these have been done over long time spans, most have not. The NOAA/NASA Pathfinder project was initiated to complement these data sets with satellite data that can provide information over larger spatial areas and longer time spans. The AVHRR Polar Pathfinder (APP) program was part of this project. The APP was to supply data from the NOAA AVHRR instruments that was consistently generated in a format usable to a wide range of scientific investigators.

A grant was obtained from the NASA Research Announcement 97-MTPE-O3 to evaluate the APP products, to provide any enhancements, and to compare with products from the new MODIS instrument. There was about a two year overlap between the projects, and this validation effort had several impacts on the APP products.

The APP products are derived from the instruments aboard 4 NOAA satellites, NOAA-7, 9, 11, and 14. Initial validation efforts compared the thermal calibrations of these instruments, and differences are found. Calibration has undergone many revisions and techniques have changed since the satellites were launched. The first calibration methods were optimized for global ocean temperatures, as this was one of the primary and important uses of the AVHRR instruments. As the APP program started, newer methods that provided more accurate temperature retrievals over a wider range of temperatures were being developed. The calibration of a wider range of temperatures were necessary because of the extremely low values in the polar regions. These methods were also designed so that calibrated data was also consistent between all the NOAA satellites. These newer calibration methods were then adopted primarily because of the initial findings of this validation effort.

Broadband albedo is one of the APP products. Studies with in.situ. data from Greenland showed poor correlation with the APP broadband albedo. A new model for deriving albedo from the AVHRR visible channels was developed. The broadband albedo product was improved. Some problems still remain, primarily because of the bi-directional reflection distribution functions that are available. The current models do not adequately account for the extreme solar and observing angles that are needed for satellite remote sensing. While albedo values appear valid for some locations, values at locations such as the South Pole are not. So, some improvement has been made, but further work is necessary for a consistent and reliable broadband albedo over all areas and under all conditions.

A third area that this validation effort contributed to was in the generation of a cloud mask. Cloud masking may be the most difficult task because of the widely varying surface conditions, limited amount of spectral information, and varying solar illumination, from continuous to no sunlight. The current cloud masking methods work fairly well for open and ice covered ocean areas, but not over ice and snow covered areas such as Greenland and Antarctica. Newer methods are currently being developed and tested.

Original plans for the APP products included subsampled broadband albedo and surface temperature images to be used for easy browse purposes. As the validation efforts

proceeded, and the ease of using images of this size, solar zenith angle, time of acquisition, and cloud mask images were also included. These images at about 25 km resolution may be useful for climatology and modeling studies.

The final area that the validation project had an impact on the APP products was in the extension of the temporal coverage. Original APP plans called for processing GAC data from 1983 to 1998. Data was obtained from several sources for the APP effort, including Goddard, JPL, NCAR, and a receiving station at the University of Colorado. When the APP project ended, data was not available for 1994 from any of these sources, and ended in August of 1998. But because of the delay in launching the MODIS instrument, further GAC data was obtained from SAA to coincide with initial MODIS polar products. To then complete a continuous data set, data was also obtained from SAA to fill in other missing time periods. The APP 5 km data set is then complete from October 1981 through the end of December 2000, with the exception of September 1994 to December 1994 when no afternoon NOAA satellites were operational. This provides a little over 19 years of climatology data, for both polar regions.

## **2. APP Products**

The APP proposal was to generate a suite of products from AVHRR data from the nominal 1 km resolution HRPT and LAC and the 5 km GAC data. The products from the GAC data spans about 19 years from 1981 through 2000 and has sets of images twice per day for both poles. The products at the higher resolution have a more limited time span because of data availability from 1992 through the present.

The most difficult part of the APP project was assembling the AVHRR data. Each data source had differing archive formats. After acquiring the data, it was subsetted to only the polar regions and put into a common level1b format. This data was then calibrated using the newest techniques. There are about 14 orbits per day that are navigated to a common grid and composited onto the EASE grid. The compositing into twice per day images was based upon local time and minimum scan angle.

The resolutions were chosen to be exact multiples with other available polar data, all on a common grid, the equal area scaleable grid (EASE). The 1 km AVHRR data was gridded to 1.25 km so as to be a factor of 4 with the 5 km products from the GAC data. The SSM/I data in the EASE grid is at 25 km, and the products from the TOVS Pathfinder are at 100 km.

The APP products are at different levels of processing. The basic set of products are the composited AVHRR channel data along with time of scan, solar zenith angle, scan angle, and relative azimuth between the sun and satellite. Further processing steps then generate a broadband albedo, surface temperature, and cloud mask. Because processing algorithms notoriously and continually change, the channel data is preserved so that researchers in the future will be able apply better methods. The acquiring, calibration and compositing steps are by far the most time consuming.

The polar regions have some unique characteristics when using satellite data. The temperatures are extremely low, winter periods have little or no sunlight, solar elevation

angles can be very low, and scan angle can be high. The better cloud masking relies greatly on the visible channels that may not be available during dark conditions. The very low sun elevations affected the broadband albedo calculations along with low satellite elevations. However, the satellite swath coverage has much more overlap in the polar regions, with full overlap at the pole every orbit. But the scan angles at the pole are larger.

Also included is a surface mask generated from SSM/I data. The surface mask shows open or ice covered ocean areas, bare or snow covered land, and ice sheets. This mask is extensively used in the production of surface temperatures and albedos, and cloud masks.

### **3. Validation**

#### **3.1 Objectives**

There were two primary goals of this validation effort. First was to assess the accuracy of the APP products in relation to ground based measurements and to examine the consistency of the full data across the multiple NOAA satellites. The secondary goal was to examine the APP products in relation to the MODIS polar products. More specifically:

- Quantify the APP accuracy and sources of error by comparing Pathfinder products with field measurements
- Determine the consistency of mean fields and trends in comparison with longer time series of available station data
- Investigate the consistency of the products between the different AVHRR instruments over the 1981–1998 period of the NOAA program
- Compare an annual cycle of the APP products with MODIS to establish a baseline for extending Pathfinder-type products into the new ESE period

#### **3.2 Consistency**

The APP products are derived from AVHRR instruments aboard 4 NOAA satellites. There are several considerations that need to be addressed. First, each satellite drifts in orbit, and the longer that each satellite remains operational, it scans the earth later each day. Next, the satellite's orbit precesses about 1 degree each day, so that a spot on the Earth is not scanned at the same local solar time every day. The final important consideration is that each instrument has different sensor characteristics.

A point near Barrow, AK was chosen to highlight these changing conditions. The time of acquisition of the data at this location is shown in fig. 1a. This figure shows the progression of the 4 NOAA instruments quite clearly and drifting times. Figure 1b shows the satellite elevation changing from day to day. Figure 1c shows the changes in solar zenith angles and figure 1d shows the changes in the relative azimuth angles.

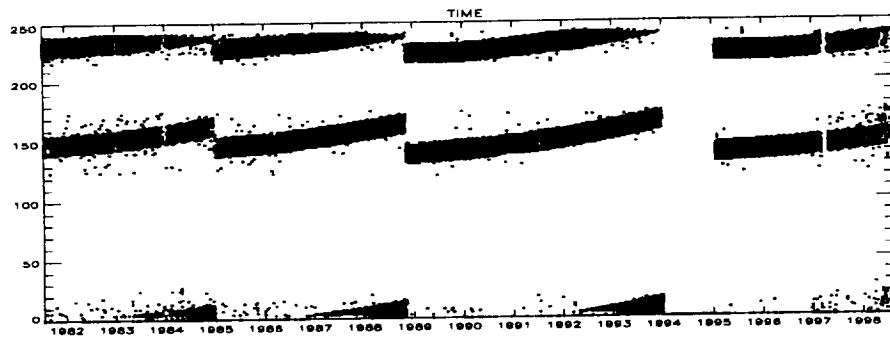


Fig. 1A Time of Acquisition

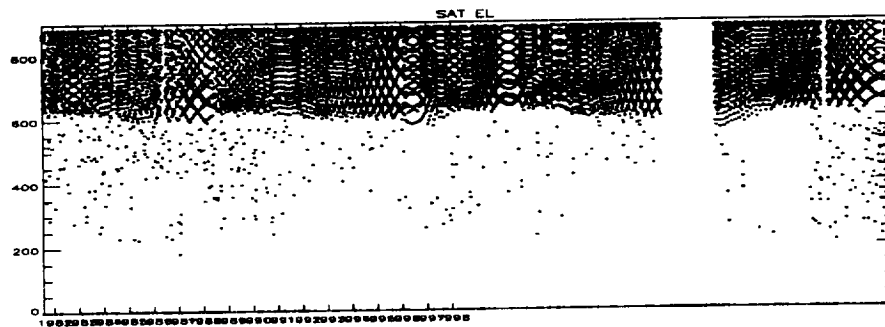


Fig. 1B Satellite Elevation

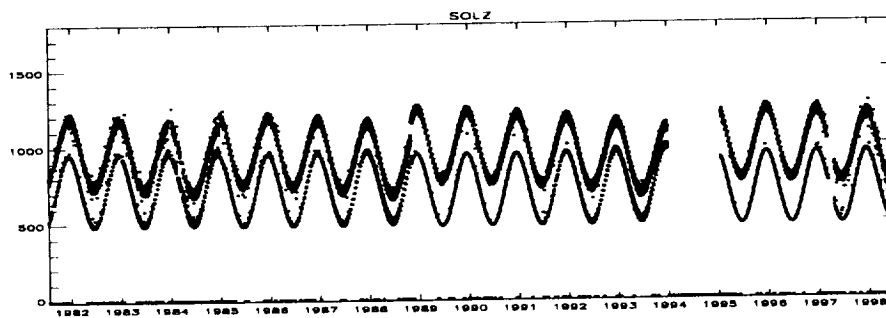


Fig. 1C Solar Zenith

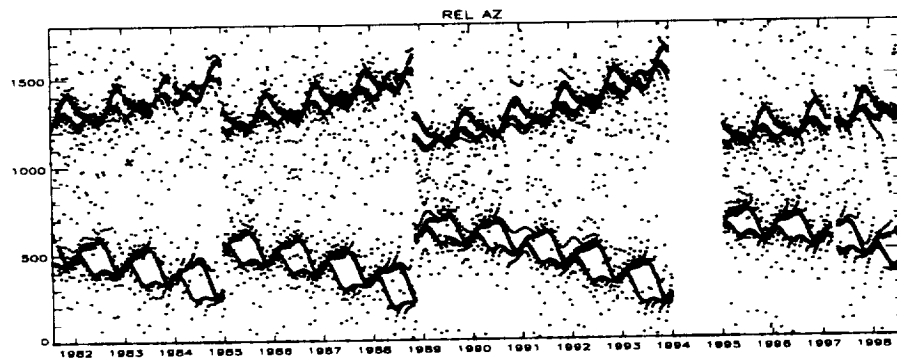


Fig. 1D Relative Azimuth

All the plots show both the morning and afternoon values, and all values are times 10. The algorithms used for retrieving surface temperature and albedo must account for these widely varying conditions.

Figure 2 is a time series of the temperature at Barrow. The plot is included to show the extreme range of temperatures encountered at this location.

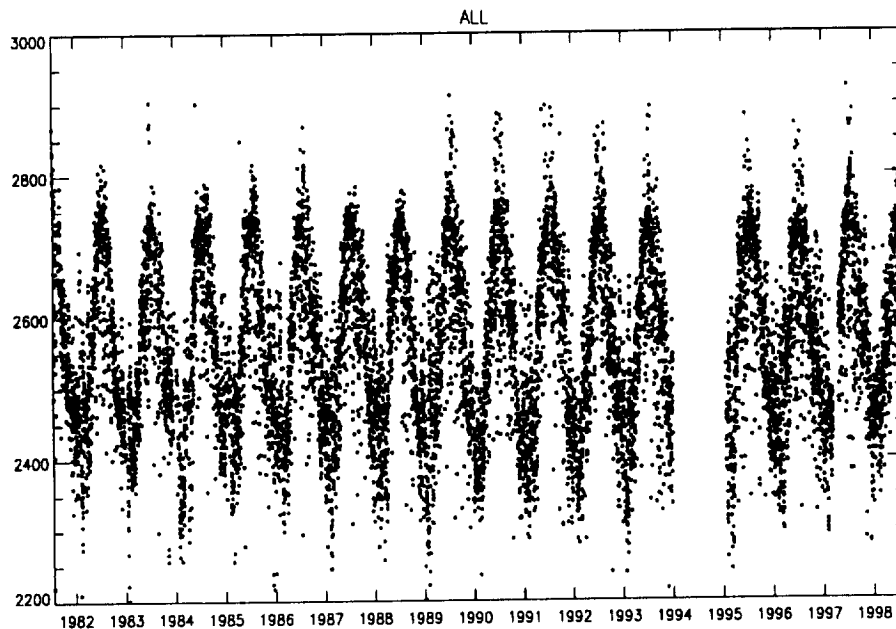


Figure 2 APP surface temperatures at Barrow, AK.

One primary goal of the validation effort is to check the consistency of the data across the multiple platforms. There was no ground measurements found that spanned the period of the AVHRR data. As a general check, an average temperature was generated for the full Arctic region. Figures 3 shows the transition period from NOAA 7 to NOAA 9. There is no apparent inconsistency. The change from NOAA 9 to NOAA 11 is shown in figure 4. The afternoon temperatures are the higher line and the morning line the lower.

The temperatures at the South Pole Station during these same periods and are shown in figures 5 and 6. Again no observable inconsistency is discernible. These are not definitive results. No check was possible between NOAA 11 and NOAA 14 due to a large gap in coverage. For a period of 4 months, NOAA 11 became inoperable before NOAA 14 was launched.

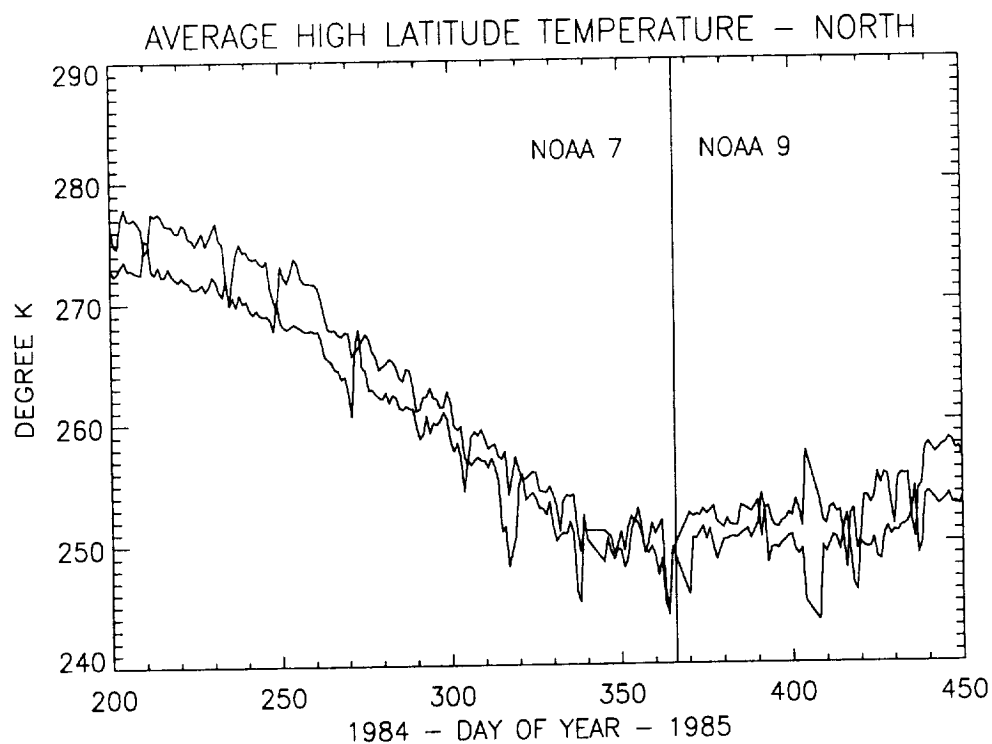


Figure 3. Average temperature during change from NOAA 7 to NOAA 9.

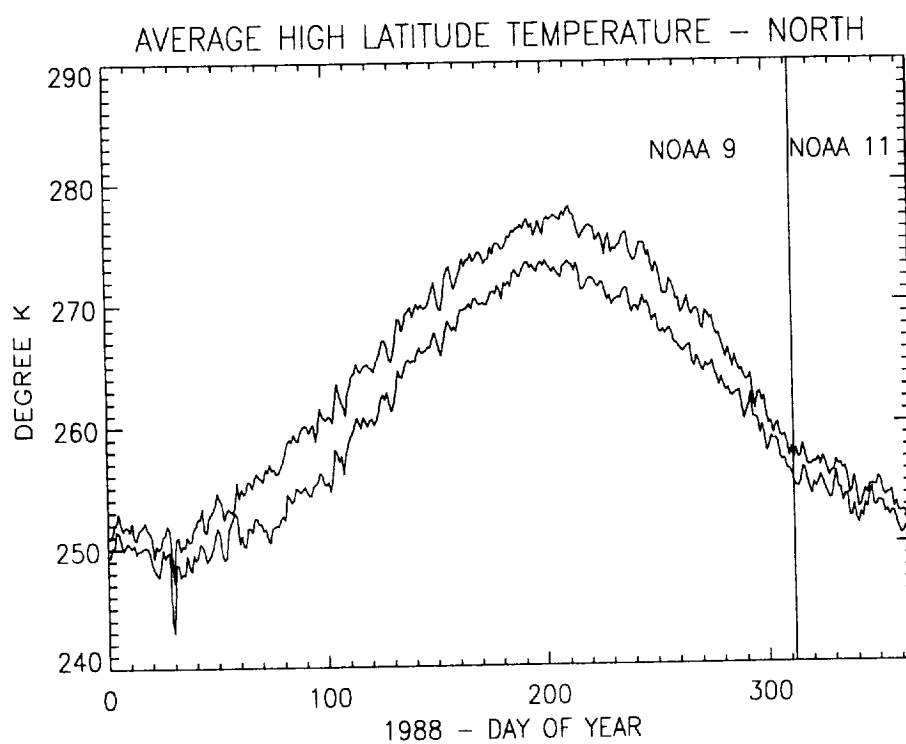


Figure 4. Average temperature during change from NOAA 9 to NOAA 11.

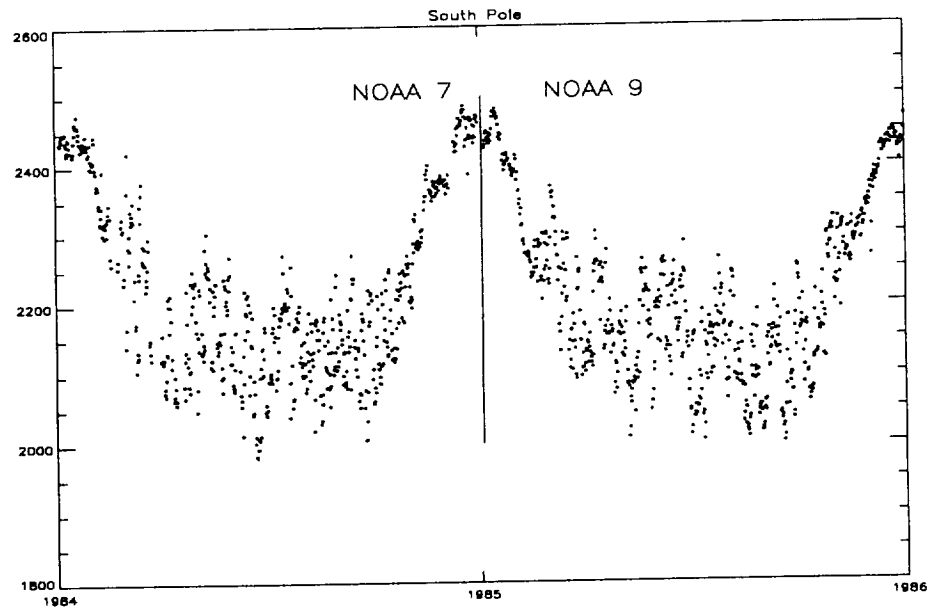


Figure 5. Temperature at South Pole Station during change from NOAA 7 to NOAA 9.

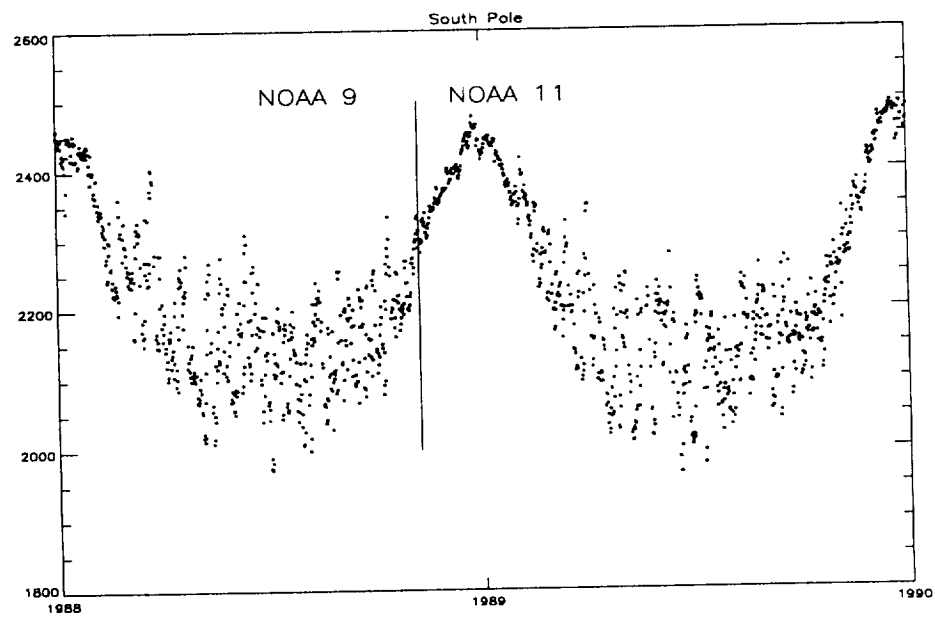


Figure 6. Temperature at South Pole Station during change from NOAA 9 to NOAA 11.



### **3.3 Greenland**

APP albedo values were compared with ground measurements from 14 automatic weather stations (AWS) on the Greenland ice sheet during 1997 and 1998. Results show that the satellite-derived values are on average 10% less than those measured by the AWS data. Because of differences in the methods (i.e. The APP values are a broadband value ) the AWS values are biased high by about 4%, the differences may only be 6%. Further work is needed to reduce this error, that may be mostly associated with current BRDF models of ice sheet surfaces. A more detailed description can be found in the attached paper:

Intercomparison Between in situ and AVHRR Polar Pathfinder-derived Surface Albedo over Greenland. Stroeve, et.al. Accepted for publication.

An extension of this work looks at the albedo for the full data set from 1981 to 1998. The analysis highlights that variations in APP albedo values are correlated with the North Atlantic Oscillation (NAO) index, and that trend analysis is in agreement with recent trends in melt and precipitation. More details can be seen in the attached paper:

Assessment of Greenland Albedo Variability from the AVHRR Polar Pathfinder Data Set.

Julienne Stroeve. Submitted to Journal of Geophysical Research.

APP temperature values were compared with values taken at the Swiss Camp in 1990 1991. The APP cloud masking currently performs poorly over ice sheets and cloudy days that show up with very low temperatures have not been removed. The comparisons, shown in figure 7 show good agreement and follow similar trends, but with a slight offset. The APP values are about 4 degrees higher.

Comparisons were done with near surface air temperatures in 1997. Again, the values seem to be well correlated, but here the APP values are biased slightly lower than the air temperatures (Figure 8).

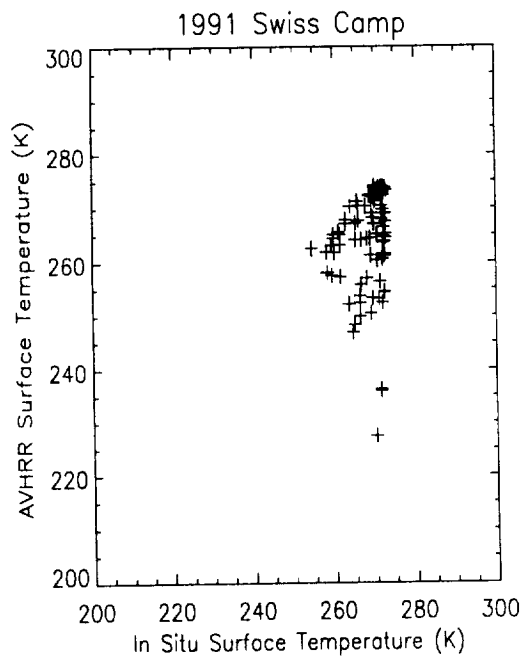
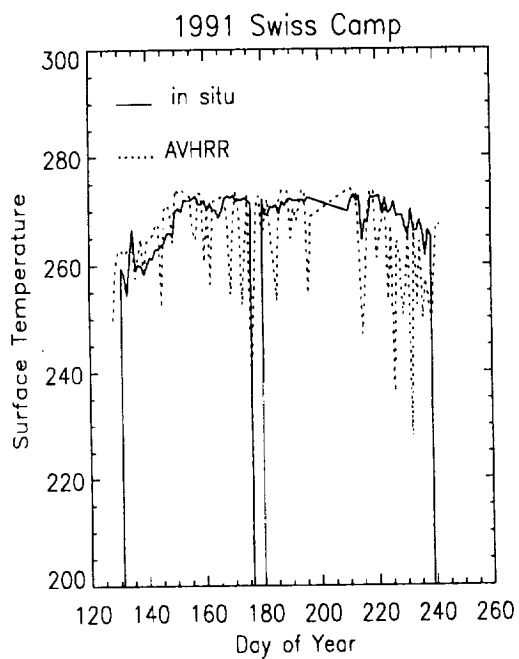
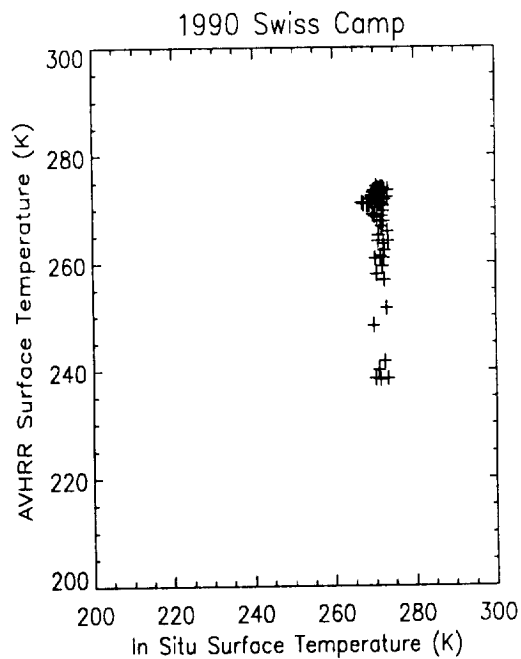
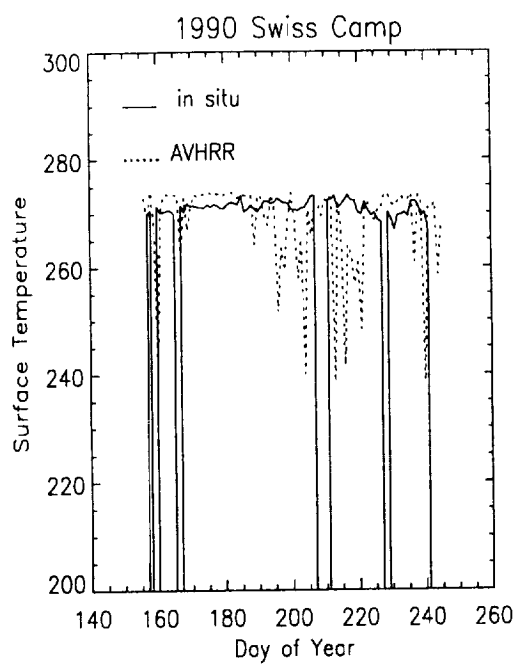


Figure 7. Temperature comparisons in Greenland.

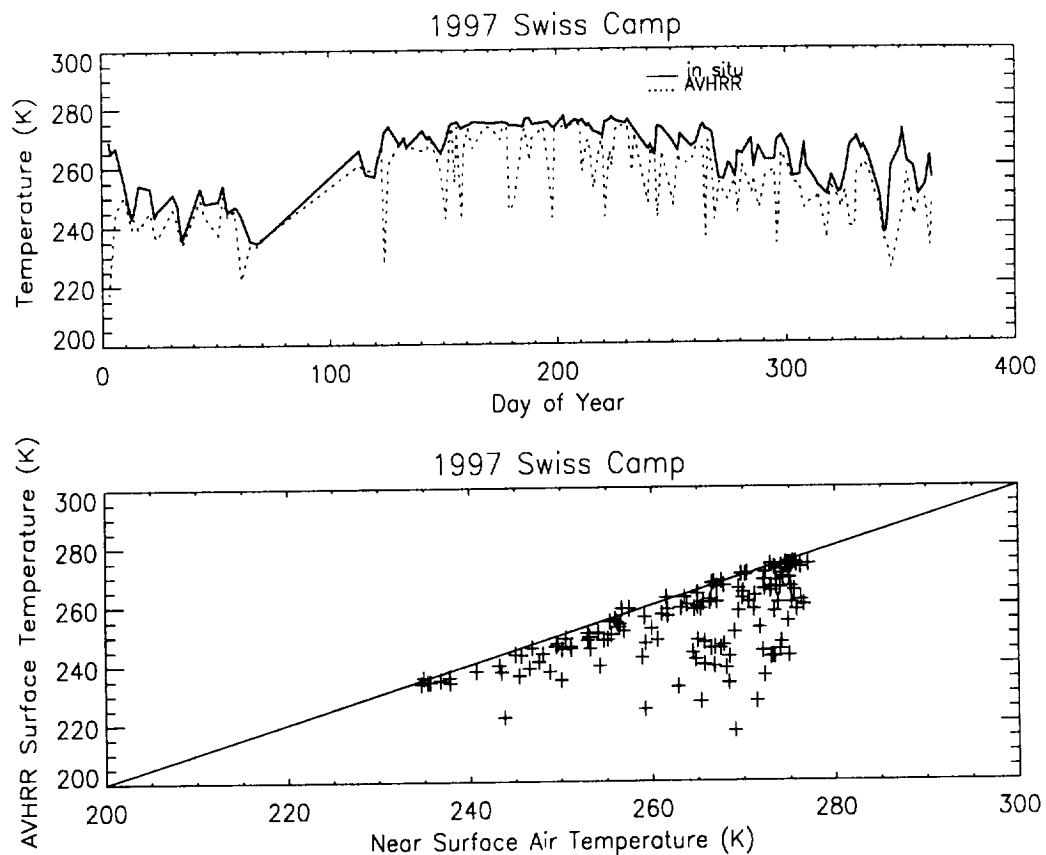


Figure 8. APP temperature vs. air temperatures.

### 3.4 South Pole Station

Ground based radiometers were obtained for the South Pole Station and compared with the APP surface temperatures. Figure 9 is a time series from 1995 to 1998 of the APP temperatures and figure 10 is for the ground measurements. As previously mentioned, the cloud masking from APP does not work well over the ice sheets and these plots include both clear and cloudy periods. Figure 11 compares the two data sets. The APP values are biased  $-1.08$  degrees compared to the ground radiometer.

While the albedo study above in Greenland showed good general agreement with ground based measurements to 6 to 10%, problems exist with albedo retrievals over the central Antarctic ice sheet. Because of the low sun and satellite elevations, albedo values can be exaggerated (figure 12). Again this is most likely due to poor BRDF models at the extreme angles.

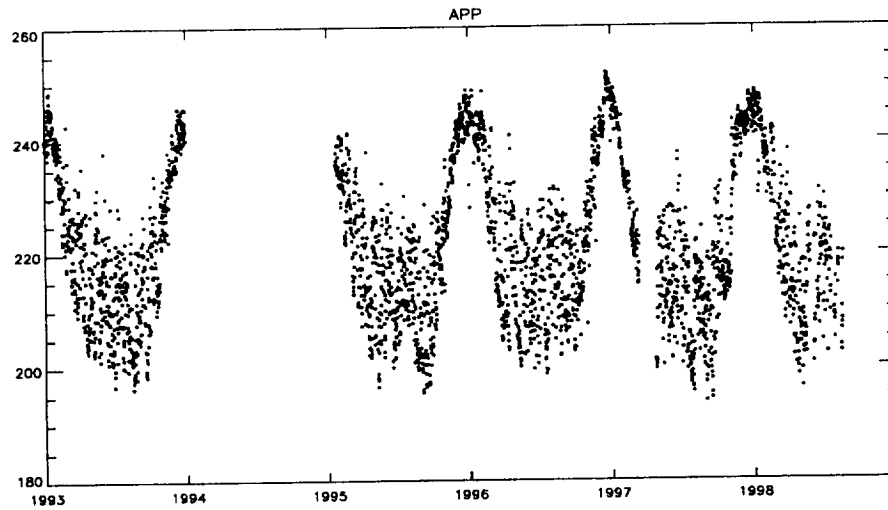


Figure 9. APP temperature at South Pole.

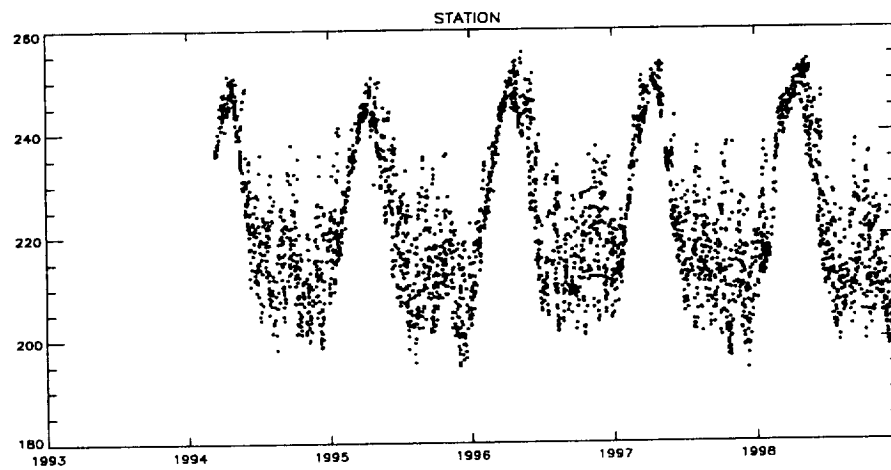


Figure 10. Station temperature at South Pole.

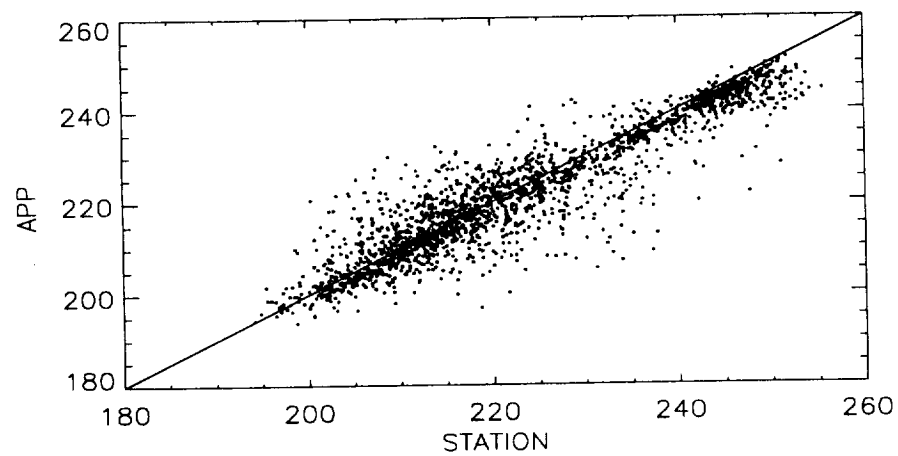


Figure 11. APP vs Station differences at South Pole Station.

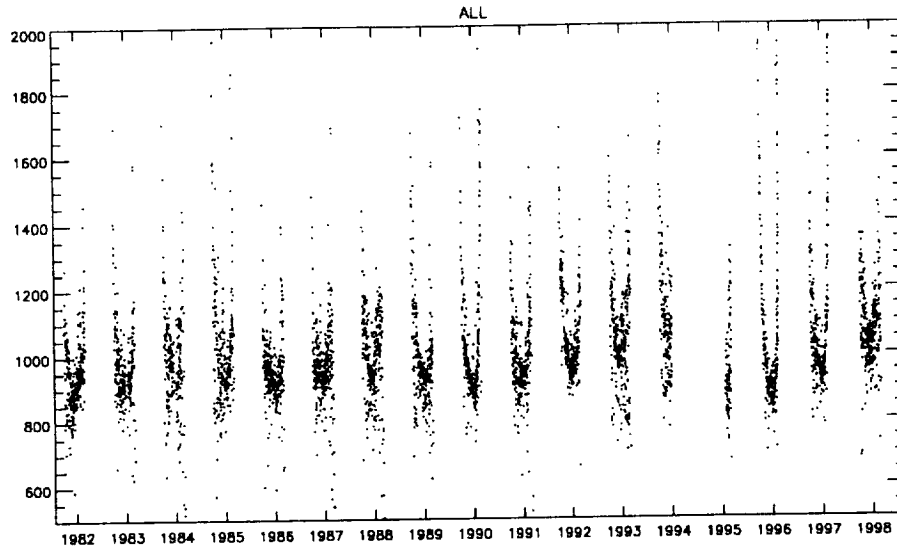


Figure 12. Albedo time series at South Pole Station.

### **3.5 SHEBA and FIRE-ACE**

In 1998 two experimental campaigns were done in the Arctic, the Surface Heat Budget of the Arctic Ocean (SHEBA), and the First ISCCP (International Satellite Cloud climatology Project) Regional Experiment – Arctic Cloud Experiment (FIRE-ACE). A more complete description of the comparisons between the ground measurements and the APP products can be found in the attached paper:

Spatial and temporal variability of satellite-derived cloud and surface characteristics during FIRE-ACE. Maslanik, et.al. In press.

This study found good agreement with the ground observations and used the APP products to extend the research to areas larger than were directly measured from the limited local sites.

### **3.6 Cloud Trends in the Arctic**

A study using the APP cloud mask products looked the complete time series from 1982 to 1987. For more detail see the attached paper:

Spatial and Temporal Variations in Monthly Averaged Cloud Cover Based on AVHRR Polar Pathfinder Data. Drobot, et.al. To be presented at upcoming AMS conference.

Monthly mean cloud fractions were similar to other studies. Trend analysis of the monthly means suggest patterns associated with changes in regional sea level pressure patterns.

### 3.7 Barrow

Surface broadband albedo, upward and downward shortwave and longwave radiation, and skin temperature estimated from the upward longwave radiation were provided by the NOAA Climate Modeling and Diagnostic Laboratory's (CMDL) meteorological tower located near Barrow, Alaska. Mr. Robert Stone of CIRES/NOAA was instrumental in collecting and providing these data. The tower is located at the CMDL observatory, approximately 8 km north-northeast of the town of Barrow. The albedos and radiation were recorded using broadband Eppley pyranometers and pyrgeometers. The albedo measurements were obtained from pyranometers mounted high on the tower, thus providing a fairly large field of view to minimize localized effects of the tower, such as the accumulation drifting snow. In addition to the tower data (provided as 1-hour means), the data set provided to us included sky cover (cloud fraction) recorded by the National Weather Service observers in Barrow, and averaged over a 3 hour period. The observation site is located within approximately 5 km of the ocean, which reduces the value of the data for comparisons during periods when open water is present near shore. In cold months though, the albedo and skin temperature of the area are expected to be relatively uniform.

The comparisons were carried out by selecting the observations from the tower data and the APP data that agreed to within approximately 2 hours in terms of sampling time (for both day and night composites), and then selecting from this set those observations for which the Barrow cloud observations indicated 0% cloud fraction. The nearest-neighbor APP skin temperatures and broadband albedos for these observations were then compared to the corresponding tower data. This subsetting by Barrow cloud fraction yielded 24 clear sky observations in 1992 (day), 13 in 1992 (night), 13 in 1993 (day) and 19 in 1993 (night). The means of differences (Barrow minus APP) were  $-0.42$  K (1992; day),  $0.35$  K (1992; night),  $1.07$  K (1993; day), and  $0.07$  K (1993; night). The 1993 day values included an a single outlier with a difference of  $8$  K. When this outlier was excluded, the mean difference for 1993 day decreased to  $0.56$  K. Overall, the bias was less than  $0.5$  K, and differences were less than  $5$  K for 85% of the paired observations. We expect that a significant portion of these paired differences are due to spatial variability in temperature between the tower measurement and the 5-km APP pixel.

Albedo comparisons were conducted in the same manner, but were complicated to a greater degree by the effects of open ocean within the APP coverage. For 1992, the tower albedos show an abrupt change in albedo associated with snow melt, from  $0.85$  to  $0.32$ . The APP data show the same progression of albedo change, but unlike the tower data, the APP albedos yield intermediate between 100% snow-covered and bare ground during the melt period. This likely reflects the larger sampling area of the APP pixels, and possibly includes the effects of near-shore sea ice and perhaps persistent ice on lakes within the pixel coverage. During the pre-melt and post-melt phases, the APP albedo averaged  $0.825$  compared to the  $0.83$  value from the tower. The APP post-melt albedo was  $0.2$  compared to  $0.32$  for the tower. Again, this lower albedo probably includes some effect from ocean and lakes in the APP field of view. In 1993, the clear-sky samples do not include the transition period, but instead show high albedos for the entire sample. Mean tower albedo was  $0.786$  versus  $0.749$  for the APP albedos. At least part of the lower APP albedo is likely due to the effects of surfaces such as buildings, roads, and

any near-shore open water.

The above analysis used the Barrow cloud observations to determine clear sky periods. We also compared the CMDL tower data with the APP data for cases where the APP cloud masking was used to define clear sky conditions. For this, we chose all observations where each of the three APP cloud detection algorithms indicated clear sky. This yielded a total of 23 clear-sky observations in 1992 (day), 20 in 1992 (night), 18 in 1993 (day) and 35 clear-sky observations in 1993 (night). The APP cloud algorithms thus yielded about half as many clear sky cases as was indicated by the Barrow cloud observations. Mean APP temperatures for these comparisons were 259.7 K (APP) and 257.0 K (tower) for 1992 daytime observations, 254.3 K (APP) and 261.8 K (tower) for 1992 nighttime observations, 257.9 K (APP) and 261.8 K (tower) for 1993 daytime, and 257.3 (APP) and 262.7 (tower) for 1993 nighttime values. The tendency for the tower temperatures to be higher than the APP temperatures may be due to the fact that the tower viewed land only, while the APP pixel included land, lakes, and probably some ocean area. To test this, we examined temperatures for pre-melt conditions only. In these cases, the difference between the APP and tower temperatures was reduced. For daytime observations in 1993 for example, mean APP temperatures were 254.5 K vs. 256.7 K for the tower data.

### **3.8 MODIS**

To allow comparisons to MODIS products, additional APP data were generated through September 2000. Unfortunately, the calibrated MODIS radiances did not become available until late August 2000, with the snow and ice products available even later. The ice products have not been publicly released as of March 2001, but we were granted permission to use pre-release products by Dr. Dorothy Hall. Due to time constraints, we were therefore limited to comparison of only a single scene. Additional comparisons are underway and will be summarized in a journal publication, but they have not been completed in time for inclusion in this report.

The comparison image set was a MODIS Level 2 tile section covering a portion of the Laptev Sea and coastline for August 25, 2000. The corresponding APP daytime composite was subsetting to match this area. Comparisons at this point were limited to skin temperatures, using the surface temperature field (the "ice surface temperature" parameter) in the MODIS sea ice product for ice and open water, and the MODIS land surface temperature product for land temperature data. Pixels for the same approximate areas over sea ice, open water, and snow-free land were examined. Over open ocean, skin temperatures in the APP and MODIS data showed the same progression of temperatures near 273 K at the ice edge, to approximately 279 K near the coast. Over open ocean, both the MODIS ice product and the APP skin temperatures use essentially the same algorithm. Over the melting sea ice, the MODIS IST ranged from 272.6 K to 274.8 K, and thus generally overestimated the likely temperature of the melting ice. APP temperatures for the same area ranged from 272.6 to 273.5 K. Over land, the APP skin temperatures were approximately 284.2 K over a portion of the Lena River delta, compared to 286.2 K in the MODIS LST product. Over a portion of the Palmyr

Peninsula, the APP temperatures averaged 283.6 K versus 284.3 K for MODIS. Given that the APP skin temperatures over land were calculated using the same algorithm as that for ice and open water, this level of agreement with the more refined and specialized MODIS LST product is encouraging.

#### **4. Summary**

This validation study highlights the reason for the NASA Pathfinder Program and the need for products such as those from the AVHRR Polar Pathfinder project. Long time series of climate parameters covering large areas have not been available in the past.

The validation effort had a direct impact on the products from the APP. Problems associated with cloud masks, surface temperatures, and albedos were found and corrected in the final products. Part of the validation effort was used to extent the APP product generation to coincide with the delay in the launch of the MODIS instrument.

Consistency of the products is of great importance, since the time series uses data from instruments aboard 4 different satellites. While the validations done were not conclusive or definitive, because of the lack of available long term data, no obvious problems were found.

Temperature comparisons done with data from Greenland, South Pole Station, SHEBA, Barrow, and MODIS compare in most cases within one or two degrees. Most of these comparisons, however, were done with data from the more recent satellites, NOAA 11 and NOAA 14. Each ground location has its own local conditions and types of instruments and were for limited time periods. More comparisons are needed, especially for the earlier periods.

There are known problems with the APP albedo values, especially in areas such as the central Antarctic ice sheet. At this time, absolute errors for all locations are not known, but the data are useful in detecting interannual trends. Work is proceeding by others to improve the BRDF models that will reduce this problem.

Cloud masking is another area for further work. Again, absolute accuracy may be poor, but the data have been shown to be of use in analyzing trends. The cloud masking procedure has been modified, and is being tested currently.

The APP program was set up to take advantage of improved algorithms. The calibrated data is available and improved products can be generated with minimal effort.